Grant AOARD-09-4136: Measuring and Ensuring Performance and Information Quality in Multi-Agent Sensor Network Systems

Final Report by Principal Investigator

Background

This grant of $35000 was awarded in July 2009 to cover the period 25 August 2009 to 24 February 2010, and was fully expended. The PI is Professor Brian D O Anderson of Australian National University (ANU) and National ICT Australia (NICTA). Co-investigators were Dr G Mao (of Sydney University and NICTA) and Dr C Yu (ANU and visitor to NICTA). Dr B Fidan of NICTA had been planned to be a co-investigator; this was prevented by serious illness and subsequent resignation. The subject matter of the grant was robust behavior of sensor networks. The document setting out the Grant/Cooperative Agreement Award included the words:

> The grantee shall investigate robustness of sensor networks. Questions to be addressed include: given a sensor network, to characterize its ability to retain a discrete-valued property in the event of loss of p nodes and q communication links; determine where a further communication link or sensor should be introduced to achieve the best improvement; and address solvability under the constraint that any sensor can communicate with only a limited number of its neighbors.

Milestones

Because the initial proposal to AOARD was more ambitious than could be accommodated, the limited funding and time resulted in a truncation of technical ambitions. The milestones which were agreed accordingly reflected the revised scope of technical content, appropriate to the funding and duration, and the desirability expressed by AOARD of coupling to US workers. They were as follows:

1. Submit paper on sensor networks retaining localizability property in event of loss of p nodes and q communication links
2. Submit paper on characterization of giant component in large scale random networks (A giant component of a network is a connected component of at least 50% of the network. In examining large scale networks, 100% connectivity is generally too demanding a requirement)
3. Conclude visit by S Dasgupta (of the University of Iowa) and provide report on expected downstream outcome
4. Submit annual report to AOARD

The first two milestones were achieved, the visit by S Dasgupta occurred (Milestone 3) and this report serves to complete the third milestone (report on Dasgupta visit downstream outcome) and the last milestone.

Summary of outcomes against milestones

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14. ABSTRACT
The subject matter of the grant was robust behavior of sensor networks. The questions to be addressed included: given a sensor network, to characterize its ability to retain a discrete-valued property in the event of loss of p nodes and q communication links; determine where a further communication link or sensor should be introduced to achieve the best improvement; and address solvability under the constraint that any sensor can communicate with only a limited number of its neighbors. Research results included 1) how sensor networks retain localizability property in the event of loss of p nodes and q communication links, and; 2) characterization of ?giant? component in large scale random networks.

15. SUBJECT TERMS
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Milestone 1. A paper [1] entitled "Redundant Localizability of Sensor Networks", coauthors C Yu, S Dasgupta and B D O Anderson has been submitted. The abstract reads as follows:

The ability to localize a sensor network is important for its deployment. A theoretical result exists defining necessary and sufficient conditions for network unique localizability (for inter-sensor range-based localization); it has its roots in Graph Rigidity Theory where sensors and links/measurements are modelled as vertices and edges of a graph, respectively. However, critical missions do require a level of robustness for localizability, ensuring that localizability is retained in the event of link (edge) losses and/or sensor (vertex) losses. This work characterizes this robustness through a novel notion of redundant localizability, which is backed by redundant rigidity. Analogously to two well-known types of result for rigidity characterization, similar results are developed for edge redundant rigidity; they are supplemented by rather fewer results dealing with vertex redundant rigidity. These results form a foundation for any further study of redundant localizability.

In summary, one could say that this paper

- Creates a framework for considering sensor network robustness problems using graph theory
- Establishes that a requirement to be tolerant of loss of p sensors is always as tough as a requirement to be tolerant of a loss of p links
- Provides a number of combinatorial characterizations for the graphs of networks which have guaranteed tolerance of multiple link loss.

A copy of this paper has been submitted to AOARD.

Milestone 2: A paper [2] entitled "On the giant component of wireless multi-hop networks in the presence of shadowing" was finalized for IEEE Transactions on Vehicular Technology and published at the end of 2009 (and was earlier supplied). The abstract reads:

Abstract—In this paper, we study transmission power to secure the connectivity of a network. Instead of requiring all nodes to be connected, we require that only a large fraction (e.g., 95%) be connected, which is called the giant component. We show that, with this slightly relaxed requirement on connectivity, significant energy savings can be achieved for a large-scale network. In particular, we assume that a total of n nodes are randomly independently uniformly distributed in a unit square in R2, that each node has uniform transmission power, and that any two nodes are directly connected if and only if the power that was received by one node from the other node, as determined by the log-normal shadowing model, is larger than or equal to a given threshold. First, we derive an upper bound on the minimum transmission power at which the probability of having a giant component of order above qn for any fixed $q \in (0, 1)$ tends to one as $n \to \infty$. Second, we derive a lower bound on the minimum transmission power at which the probability of having a connected network tends to one as $n \to \infty$. We then show that the ratio of the aforementioned transmission power that was required for a giant component to the transmission power that was required for a

connected network tends to zero as $n \to \infty$. This result implies significant energy savings if we require that only most nodes (e.g., 95%) be connected rather than requiring all nodes to be connected. This result is also applicable for any other arbitrary channel model that satisfies certain intuitively reasonable conditions.

In summary, one could say that this paper:

- Shows that in random networks with large numbers of nodes, great savings on energy can be achieved by not maintaining transmission levels to secure 100% connectivity, but allowing instead for connectivity of say 95%.

Milestone 3: S Dasgupta visited for approximately three weeks in 2009, and the most obvious outcome of this visit was the paper whose submission is reported under *Milestone 1.* Further outcomes of this visit are as follows:

- A new PhD student, hired using funds provided by the AOARD grant, is working on robustness in sensor networks. He is focusing on the issue of vertex loss as opposed to link loss (which was the primary focus of the paper coauthored with Dasgupta). Conditions are being sought, and some have been obtained, guaranteeing the preservation of localizability when vertex loss occurs. It is hoped to submit the first paper on this work within two months.
- The PhD student has developed a work program to explore a number of other issues beyond simply coping with vertex loss.
- Professor Dasgupta will be working briefly with this student and Dr Yu, and for a more extended period with Dr Mao, during a visit tentatively planned for June 2010 (contingent on funding), with a view to carrying the ideas forward.
- A conference paper summarizing the results of the work with Dr Dasgupta is planned for submission to an IEEE Conference scheduled for Atlanta in December 2010.

Further Related Activities

- The CI made a visit to Yale University in November 2009 for joint research with Professor A S Morse and students on material related to this grant, and some of the ideas arising from that interaction have been included in a preliminary proposal to AOARD for a further (continuation) grant.
- A new PhD student (that referred to above under *Milestone 3)* started on the project in late 2009

Furthermore, without specific requirements embedded in the milestones, or the special application of funds, the team has considered problems along the following lines:

- Properties of random networks in which certain powerful nodes, e.g. base stations or a subset of nodes connected to each other via point-to-point wireless links, are connected by a backbone infrastructure, and the remaining nodes are considered connected in the event that they are

connected to any one node. This is an uncommon style of model in terms of theoretical study, but at the same time appears to better capture many physical networks. Two papers summarizing the results of the above work has been accepted for publication in IEEE ICC and submitted to IEEE Transactions on Parallel and Distributed Systems respectively [3,4].

- Related work has considered connectivity properties of one-dimensional vehicular networks, where the vehicles are not all travelling at the same speed, and individual vehicles are needed to provide intermediate relays between a source and destination. Two papers are being prepared for submission to IEEE Globecom and IEEE Transactions on Vehicular Technology respectively.
- Propagation of localization error in 1D sensor networks has been studied; it is hoped that the results will provide a pointer to error propagation in 2D networks. Nevertheless, 1D networks arise in some vehicular networks (limited access roads for example), tunnels, pipelines, etc. A paper has been submitted [5]
- During a visit by A S Morse (Yale University) early in 2009, work was commenced on *gossiping* problems; these are problems where there is an underlying physical network, in which each node stores a value of some variable of common interest. In accordance with a graphical structure associated with the network, adjacent nodes are required to share and indeed average their values on a pairwise basis (this is a '*gossip*'), with at most one node pair doing so at each time instant. The overall goal is for all nodes to learn the average of the initially stored values of the variable of common interest. The work has two novel developments: the first is the observation that if the underlying network is a tree, and if gossiping occurs periodically, with each edge in the tree gossiping once in a period which delivers a surprising property, then the convergence to the average value is independent of the ordering of the individual gossips. Secondly, the rate of convergence to the average value can be calculated just in terms of the geometry of the tree. The ideas were taken further during a November 2009 visit by the CI to Yale University. Meanwhile the first paper on this work is to appear in a book celebrating the 60th birthday of Professor Y Yamamoto of Kyoto University. [6]
- A new technique for sensor network localization appears to be very promising: it relies on counting the number of neighbors of each sensor in a fairly dense random graph, and using the numbers arising in such counts to estimate the distance between sensor pairs. Connectivity-based approaches to sensor network localization are not new, and fill a useful gap when actual distance data is not available; our approach of estimating individual intersensor distances using connectivity allows modification of connectivity-based algorithms for sensor network localization, with clear improvement: the technique we have developed appears to clearly outperform other popular methods that depend on connectivity data as distinct from actual distance measurement. This work has recently been submitted [7].

Summary of Research Direction—Long Term

The above further work is all consistent with our long term objective, set out before to AOARD, but repeated here for convenience. We are currently seeking further support from AOARD to pursue this agenda.

Collections of sensors, often mobile, are frequently being used for surveillance and relating of data. The associated networks may be unreliable or subject to attack. The research is aimed at

- Characterizing the performance of the network for achieving its designated task
- Characterizing its fragility or vulnerability to loss of agents or communication links

In particular, it seeks to

- Characterize the ability to a sensor network to retain a discrete-valued property such as connectivity, k-connectivity, or localizability in the event of loss of p nodes and q communication links
- Identify where best to introduce an additional link or sensor
- Consider other performance measures than the discrete-valued examples, such as localization error
- Identify guidelines for the proportion of a network that are anchors, in order that a given performance can be achieved
- Where possible, provide answers to the above questions that involve local information sensing and propagation to the greatest extent possible
- Extend the analysis to mobile agents

Publications

[1] Yu, C., Dasgupta, S. and Anderson, B.D.O., **Redundant localizability of sensor networks,** submitted for publication to SIAM Journal on Discrete Mathematics

[2] Ta, X., Mao, G., Anderson, B.D.O., **On the Giant Component of Wireless Multi-hop Networks in the Presence of Shadowing,** IEEE Trans on Vehicular Technology, Vol. 58, No. 9, pp. 5152-5163, November 2009.

[3] Ng, S.C., Mao, G., and Anderson, B.D.O., **Properties of 1-D Infrastructure-based Wireless Multi-hop Networks**, accepted in IEEE ICC 2010

[4] Ng, S.C., Mao, G. and Anderson, B. D.O. **On the Properties of One-Dimensional Infrastructure-based Wireless Multi-hop Networks**, submitted for publication in IEEE Transactions on Parallel and Distributed Systems,

[5] Huang, B., Yu, C., Anderson, B.D.O., **Analyzing error propagation in 1-D sensor network localization,** submitted for publication to IEEE Trans. on Aerospace and Electronic Systems.

[6] Anderson, B.D.O., Yu, C., and Morse, A.S., **Convergence of periodic**

gossiping algorithms in "Perspectives in Mathematical System Theory, Control, and Signal Processing", eds. S. Hara, H. Fujioka, Y. Ohta and J.C. Willems, Springer Lecture Notes in Control and Information Sciences, to appear.

[7] Huang, B., Yu, C and Anderson, B.D.O., **Estimating distances by connectivity in wireless sensor networks,** submitted for publication to IEEE Transactions on Signal Processing.